LONG-LIVED IN-SITU SOLAR SYSTEM EXPLORER (LLISSE)

Potential Contributions to the next decade of Solar System Exploration

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Introduction: Venus, while having similar size, mass, and location in the solar system to Earth, varies from Earth in many ways and holds many scientific mysteries despite many missions that have focused on it in the past. Primary differences include Venus' climate, atmosphere, and perhaps most notably the extreme surface conditions. The layers of sulfuric acid clouds and high pressure CO_2 laden atmosphere make remote sensing at Venus much less effective than at other solar system bodies. In addition, surface conditions present formidable engineering challenges due to the high temperature, pressure, and reactive chemistry. To date, landed missions have not been able to last more than about 2 hours on the surface [1]. This has resulted in significant knowledge gaps about the surface conditions of this important body in the solar system. The science community has effectively no in-situ temporal data at the Venus surface. These data are critical for the development of a thorough understanding of Venus' weather and the processes by which chemical species interact with each other and are transported throughout the atmospheric column.

Advances in technology, such as Silicon Carbide (SiC) based electronics and sensors, have matured to a state where a simple but powerful long-life scientific probe is feasible for Venus. An entire self-contained lander is being developed by integrating high temperature subsystems together like power, avionics, communication, structure, and an instruments / sensor payload. Combining such a system with a novel operations approach is what LLISSE is doing.

The LLISSE platform, and its variants, are a foundation for future mission concepts based on a core set of long-lived technologies providing significant new science as well as demonstrating new technical capabilities. After completion, LLISSE has the potential to be a complementary element to missions going to Venus and would provide unique and important science to missions whether they be orbiters or short duration landers.

Science Objectives: LLISSE focuses on science that 1) stands most to benefit from long duration surface operations and 2) can be accomplished with low energy and data budget. Fortunately, key measurements to get at the science objectives listed below (Table 1) match very well with LLISSE capabilities. Meteorology data is relatively low in data volume both in terms of a single measurement and also in the required sampling rate. The same is true for radiance measurements. By using a set number of micro-electro-mechanical sensors (MEMS) based chemical sensors, atmospheric specie abundances over time can also be measured in a way that meets LLISSE criteria.

Table 1 reflects LLISSE science objectives and traceability. All the measurements are consistent with the focus and approach that is uniquely LLISSE. Of course, all are traced to the current version of the planetary science decadal survey report and VeXAG guiding documents. The key questions addressed by LLISSE include better knowledge of super-rotation of the atmosphere (Goal 1, Objective B), the climate and its evolution (Goal 1, Objective B), and surface – atmosphere interaction/weathering (Goal 3, Objective B).

Table 1: LLISSE Science Objectives

Decadal Survey Goals	LLISSE Science Objectives	Measurements	Instrument Requirements

A) Define the current climate on the terrestrial planets	1) Acquire temporal meteorological data	Measurement of pressure, temperature, wind speed and direction and radiance	3-axis wind sensor measurements, radiance
	2) Estimate momentum exchange between the surface and the atmosphere	Same as above	Same as above
B) Understand chemistry of the middle, upper and lower atmosphere	3) Determine the key atmospheric species at the surface over time	Measure the abundance of gases H_2O, SO_2, CO, HF, HCl, HCN, OCS, NO, O_2	Chemical sensor measurements
C) Determine how solar energy drives atmospheric circulation and chemical cycles	4) Determine the rate of solar energy deposition at the Venus surface	Measure incident and reflected solar energy	Measurements of radiance

Development Plan and Status:

Development toward a lander having Engineering Model (EM) fidelity is ongoing. Engineering Model here describes a product which has similar form, fit, and function as a space flight version but without the all the flight materials, hardware rigor, process controls, or cost. The current development plan calls for the EM hardware to be built and tested for life and performance in Venus conditions by end of 2023. This version would be a primary battery powered LLISSE with a life goal of 60 days and communicating at ~100 MHz at power levels that would support a communication link to an orbiter at ~70,000 km above the Venus surface.

While the LLISSE project is only a couple years old, it should be noted that the background capability and some of LLISSE's components have been developed for years by other aerospace projects like jet engine development. The Venus specific application is relatively recent though and is the focus of the rest of this discussion.

Tremendous progress on several key areas has been made in the couple years since LLISSE, as a project, was started. For example, a key goal is to drive up electronics complexity to enable avionics that could control all lander functions. Integration of the increasingly complex electronics into fewer integrated circuits (IC) allows for a simpler system and lower power needs. Since project start, devices per IC as increased by ~ 2 orders of magnitude, and is nearing the level required to complete the mission. At the sensor level, versions of all sensors that were part of the original sensor suite have been developed and tested for the full 60 day life goal. Some sensors have already successful completed that level of testing. Some sensors are at lower maturity, due primarily to being added later in the schedule, yet they too continue to progress.

The communication system is one of the critical subsystems and many of its components are in development. Tests have been conducted on materials compatibility, and basic functionality for some of the components. The power driver components are in design and fabrication and will be tested in the coming months.

The primary battery is another critical subsystem. Work has focused on refining chemistry to not only function properly at the Venus conditions but also minimize self-discharge in order to support the 60 day operating goal. Life testing of battery chemistry has shown a greater than 4 fold improvement in expected life since projevt start although that is not yet enough to support a full 60 day mission. Work continues on further chemistry improvements and also on packaging of multi-cell configurations.

Structure, interconnections, and other aspects such as material selections also continue to make progress. Figure 1 shows a recent setup in a simulation chamber at NASA Glenn known as GEER (Glenn Extreme Environment Rig). This activity was undertaken to test how the GEER system interacts with the varying components and how the components interact with each other. The ongoing work is building up to a full system level demonstration in the coming months.

Figure 1 Recent test setup of LLISSE components in GEER

After a successful demonstration test, focus will be on completing the electronics and communications that support higher operating frequency, lowering power demand of the electronics, improving the battery self-discharge rate and battery packaging, and completing the balance of the sensor development. A full performance system demonstration with breadboard level fidelity hardware is planned for late 2021 / early 2022.

It should be noted that modeling, design, and materials selection and compatibility activities have been going on for a wind powered version of LLISSE as well. While design work as occurred, little hardware testing for the turbine or generator aspects have been conducted to date. This is primarily because it is expected that first LLISSE users will prefer the battery version due to lower perceived risk most mostly due to the uncertain nature of the Venus surface winds. One of the contributions a battery powered LLISSE would make is to quantify long term surface wind speeds and thus inform decisions on benefits and requirements for the wind power version of LLISSE.

More detailed discussion of the LLISSE concept / and its subsystems: LLISSE is a small (~ 10kg) yet completely independent lander. The LLISSE project includes the design and development of the lander and its instruments / sensors. Measurements will be made of temperature, pressure, wind velocity and direction, incident and reflected solar radiation, and chemical composition [2].

Figure 2. Early concept of potential wind powered version of LLISSE

These sensors will take measurements periodically (currently assumed to be every 8 hours). However, for the final flight version, timing of measurements will be determined in coordination with orbiter LLISSE communicates to. LLISSE life would cover the duration of a Venus day-light period including the terminator at one or both ends of that period. The goal of LLISSE is to operate in Venus conditions for approximately 60 Earth days.

Capabilities that enable LLISSE include:

- High temperature Sensors, Electronics, Communications, and Power Generation
- Low power and data volume science measurements
- Creative operations approach, simple periodic data transmissions coordinated with orbiter.
- High fidelity test/validation capability, in particular the Glenn Extreme Environment Rig (GEER) Figure 3. [3]

Advancements in high temperature electronics are particularly enabling for LLISSE. Si-based electronics generally used on missions do not operate at Venus temperatures [4] so this implies a need to use wide bandgap electronics, such as SiC. SiC has been chosen for LLISSE due to the design choices available in a small package, their capability to withstand harsh environments for potentially prolonged time periods, and the ability to form complex integrated circuits (IC's).

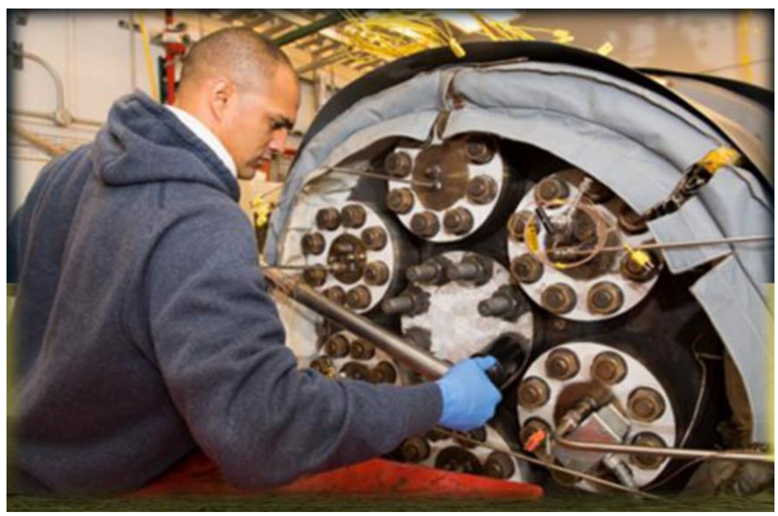

Figure 3. Testing in GEER at Venus surface conditions

Recent work has notably expanded capabilities and produced the world's first microcircuits of moderate complexity (Medium Scale Integration). These have been shown to operate for thousands of hours at 500˚C [5-8] as well as operation in Venus simulated condtions for up to 60 days.

Other subsystems are making progress as well but will not be discussed in detail. Rather, to better convey status to readers, a table on technology readiness has been prepared and shown in Appendix B. The table in the appendix reflects current TRL levels for various key elements of LLISSE. It should be noted that the TRL levels shown are a notional assessment because a specific mission has not been selected, nor a launch vehicle or the specific orbiter or orbit parameters. Since these are all unknown at this time there is no way to technically achieve a TRL 6. However, given where the challenges lie for Venus surface landers a reasonable TRL 6, for purposes of this document, is to show that the lander and its subsystems will operate nominally at Venus surface conditions for the 60 day life goal.

LLISSE and Potential Applications: A scientifically significant and programmatically exciting application of LLISSE could be to serve as the "long-lived station" complementing a Venus orbiter or short duration lander. LLISSE is deliberately designed to be a supportive element on other missions to Venus, either orbiters or landers. The small size and mass, its self-contained approach (Figure 4 and 5), and its complementary and compelling contribution of temporal science make it a good candidate for inclusion to competed missions proposed to Discovery or New Frontiers calls or on missions led by other governments. For example LLISSE is part of the baseline Venera-D mission concept and would be attached to and support the main lander science.

LLISSE could readily be inserted into a small entry shell like Pioneer Venus and become a complementary element to an orbiter (Figure 5). In such a scenario, the interfaces with the orbiter would be very simple. Physical connection would be through a commercially available spin table and would require only a release function by the spacecraft during the cruise stage. The only other interface would for the orbiter to receive the RF signal from LLISSE and relay it to Earth.

One final aspect of LLISE to highlight is that there are opportunities to vary the capability and purpose of LLISSE. A series of studies have shown the viability of using the core LLISSE technologies, but adapted to different platforms to meet specific science or technology objectives. Figure 4a-b) shows illustration of battery and wind powered versions of LLISSE respectively. Figure 4c) shows a modified and enhanced LLISSE, called Seismic and Atmospheric Exploration of Venus (SAEVe) lander [9] which targets interior and atmospheric studies by adding a seismometer, heat flux measurement, and short-lived cameras to the basic LLISSE payload. Figure 4d) shows the ~$200 M Venus Bridge Orbiter and Surface System (V-BOSS) concept [10, 11] which is targeted for coordination with an orbiter for even better science return e.g., IR imaging coupled with IR bolometers at the surface as well as localized chemistry and composition measurements.

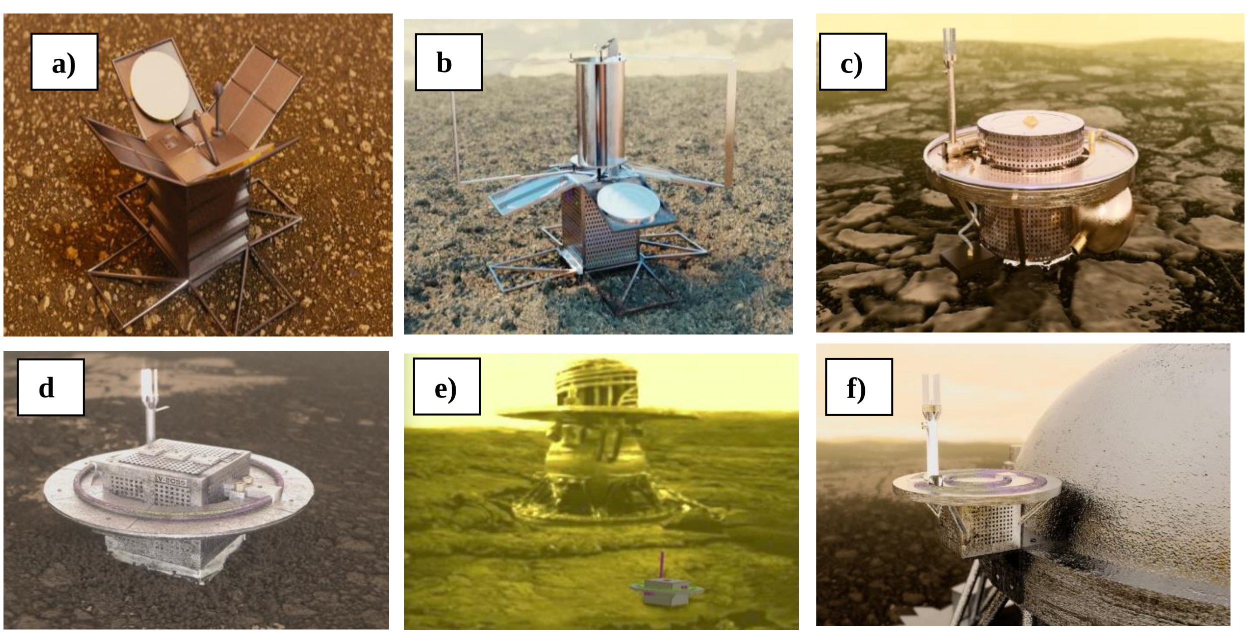

Figure 4. Artist's conception of the LLISSE platform and its various embodiments: a) Early concept for a battery powered LLISSE after deployment; b) Wind powered LLISSE after deployment; c) SAEVe lander; d) V-BOSS lander; e) Notional comparison of the V-BOSS lander to a Venara lander; f) A version of LLISSE mounted on a traditional, larger lander.

Figure 5: Conceptual Technology Demonstration veriosn of LLISSE (released from an orbiter)

As mentioned, various versions of LLISSE can be envisioned: a tech demo version, (which would demonstrate the basic ability to survive and communicate from the surface of Venus) Figure 4: the LLISSE version in development (60 day life with scientifically relevant measurements); more sophisticated versions as captured in the recent SMD funded planetary small sat study like the SAEVe lander; or the Venus bridge study lander/orbiter pair, called VBOSS. The more sophisticated versions of LLISE, which have larger mass and volume but also increased life and more instruments such as seismometers, cameras, and other sensors or instruments.

Conclusion: LLISSE is a novel and exciting small Venus lander, that is in development through testing of EM fidelity hardware. LLISSE would have the potential to provide the first ever temporal science from the surface of Venus to allow us to get new measurements that help address climate / weather, energy balance, and surface / atmosphere interaction questions.

LLISSE is designed to be a complementary element for most any other Venus orbiting or landed mission. It is relatively easy to integrate and has minimal impact to its partner mission. It can be scaled from a technology demonstration item to more a sophisticated scientific element that may address unique and compelling science potentially even seismology and local morphology.

If all goes as planned, the life and performance capability of a scientifically interesting LLISSE will be demonstrated by end of 2023 and, if successful, can transition to a flight build supporting missions in the mid 2020's. A simple technology demonstration version could be available even sooner if efforts were focused in that direction.

Appendix A: References

References:

[1] Venus Flagship Mission Study (2009)

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[6] P. G. Neudeck, et al., "Yearlong 500°C Operational Demonstration of Up-Scaled 4H-SiC JFET Integrated Circuits", Journal of Microelectronics and Electronic Packaging, vol. 15, 163, 2018

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[10] G. W. Hunter, V-BOSS: Venus Bridge Orbiter and Surface System Preliminary Report, Fifteenth Meeting of the Venus Exploration and Analysis Group (VEXAG), https://www.lpi.usra.edu/vexag/meetings/archive/vexag_15/presentations/21-COMPASS-Venus-Bridge-Summary.pdf, November (2017)

[11] R. Grimm and Martha Gilmore, "VEXAG Venus Bridge Study" presentation to the SMD Associate Administrator, https://www.lpi.usra.edu/vexag/reports/Venus_Bridge_Summary_Slides.pdf, April (2016)

Appendix B: Technology Readiness for LLISSE and Potential Augmentations

Technology	Current TRL	Funding Source: Ongoing (O) (to TRL 6) and Potential (P)
Electronic circuits (SiC): sensors and data handling	4-5	LLISSE (O)
Electronic circuits (SiC): power management	3-4	LLISSE (O)
Communications (100 MHz)	3-4	LLISSE (O)
Wind Sensor	4	LLISSE (O)
Temperature Sensor	5+	LLISSE (O)
Pressure Sensor	4-5	LLISSE (O)
Chemical Sensors	5	LLISSE/HOTTech (O)
LLISSE Bolometer	3-4	LLISSE (O)
Seismometer	3	LISSE (O) and possibly MaTISSE (P)
Camera / imaging System	4-5	Rocket University (O) Than MaTISSE (P)
Solar Radiance	4	MaTISSE (P)
High-Temperature Battery	3-4	LLISSE and HOTTech (O)
Entry Shell	6	HEET – need Venus specific design